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# TECHNICAL NOTE

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# EXPERIMENTAL EVIDENCE FOR THE PRESENCE OF HELIUM IONS IN THE UPPER ATMOSPHERE BASED ON EXPLORER VIII SATELLITE DATA

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by

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SUMMARY

Values of positive ion concentration ($N_+ = 1.3 \pm 0.1 \times 10^4$ ions/cm$^3$), electron temperature ($T_e = 1750° \pm 200°K$), and the ratio of atomic helium to oxygen ions ($He^+/O^+ = 1.3 \pm 0.3$), measured by three separate experiments at an altitude of 1630 km on the Explorer VIII satellite, (1960$\xi$) are presented. These, together with ionosonde data, are shown to be consistent with a model of an isothermal upper ionosphere in diffusive equilibrium. This model implies that hydrogen ions are less important than both helium and oxygen ions at altitudes below 1600 km. The measured ratio of helium to oxygen ions is consistent with that postulated by Nicolet in 1961.

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## INTRODUCTION

The Ionosphere Direct Measurements Satellite, Explorer VIII (1960ξ), was launched from Cape Canaveral, Florida, on November 3, 1960, into an orbit with a 50 degree inclination to the equator; its planned active life was two months. The project was initiated as a result of proposals by Bourdeau and Clark and also by Pearse and Bennett to the National Academy of Sciences in 1958. Significant changes in the experiments as originally conceived were made in accordance with the theoretical work of Whipple (Reference 1) and exploratory rocket flights (Reference 2).

As the name implies, the satellite contains a family of plasma probes designed to measure the characteristics of charged particles with thermal energies. A fundamental characteristic of these plasma probes is the use of one or more grids placed in front of a collector, arranged in concentric planar geometry. Satellite-borne gridded probes were first used successfully by the USSR (References 3, 4) on Sputnik III (1958δ). The USSR work, which is characterized by the use of spherical geometry, has been extended to studies of extremely low charged particle densities in the interplanetary plasma (Reference 5).

Two of the Explorer VIII plasma probes were designed to measure electron temperature in a quasi-redundant fashion. A third was designed to measure positive ion concentration by monitoring the positive ion current which flows from the ionosphere to the spin-stabilized satellite as the latter rotates. The fourth was designed to measure the mass

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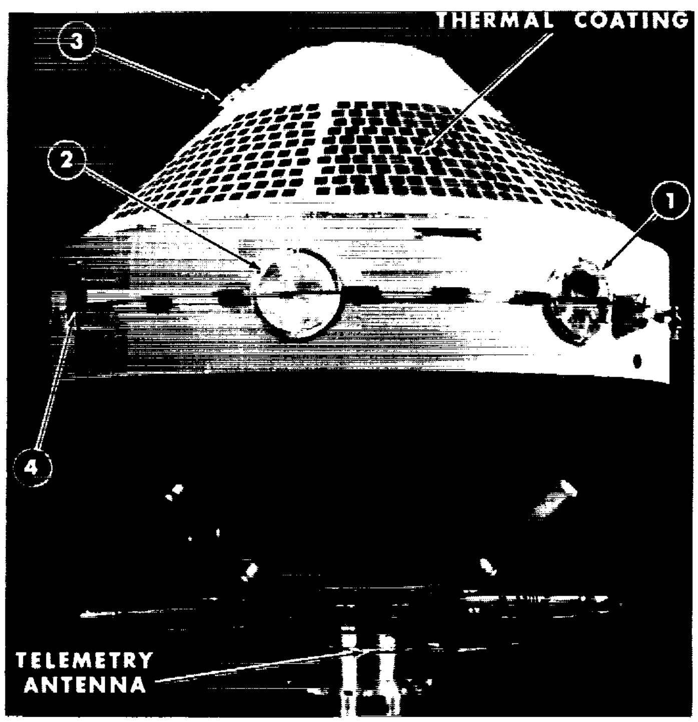
distribution of positive ions from the behavior of the positive ion current as a function of an applied retarding potential when the sensor was pointed in the direction of motion.

The success of experiments of this type depends upon an evaluation of the interaction between the spacecraft and the ionized atmosphere which immediately surrounds it. A descriptive model of this interaction, based on data from the aforementioned experiments and two additional probes flown on the satellite specifically for this purpose, is found in Reference 6. This model is consistent with that postulated by Gringauz and Zelikman (Reference 7).

One of the primary geophysical missions of the satellite, in addition to obtaining representative values of charged particle concentration, was to test thermal equilibrium by comparing measured electron temperatures with neutral gas temperatures computed from satellite drag observations. Another important objective (Reference 8), the main topic of this report, was the determination of the characteristics of the coupling region between the upper ionosphere and the magnetosphere.

A photograph of the satellite, showing the location of the three sensors pertinent here, is presented in Figure 1. The aluminum shell, consisting of two truncated cones joined at




1. RETARDING POTENTIAL PROBE
2. ION CURRENT MONITOR
3. ELECTRON TEMPERATURE PROBE
4. ASPECT SENSOR

Figure 1 – The Ionosphere Direct Measurements Satellite (Explorer VIII)

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their bases by a short cylinder, is 30 inches in diameter at the equator and 30 inches high. Both cones are covered with non-conductive thermal coatings in a pattern conducive to the maintenance of an equipotential surface. Yo-yo despin wires, jettisoned after they had slowed the satellite spin rate to an orbital value of 21.4 rpm, are shown encircling the satellite at the equator. A combined solar-horizon sensor provided supporting information on the satellite orientation.

The data presented here were obtained when the satellite's spin axis was very nearly perpendicular to the direction of motion, an orientation favorable to the determination of ionic characteristics. Three parameters (ion concentration, electron temperature, and the ratios of ionic constituents) measured at the satellite altitude, together with ionosonde data taken at the same time south of the satellite's geographic position, are sufficient to compute an electron density profile from the F2 peak to the satellite altitude. All the data reported here were obtained at 1115 UT on November 24, 1960, when the satellite was at an altitude of about 1600 km and at 75°W, 32°S.

## MEASURED VALUES OF ELECTRON TEMPERATURE AND DENSITY

The primary Explorer VIII electron temperature experiment is a simple modification of the classic Langmuir probe in that two electrodes (a collector located behind a grid mounted flush with the satellite skin) are used instead of one. It represents the first space flight of this type of device in which the effects of positive ion and photo-currents have been removed experimentally. This approach was taken because of uncertainties in correcting for these unwanted currents when interpreting the classic Langmuir probe volt-ampere curve. A detailed description of the experiment, together with an evaluation of the effects which the interaction of spacecraft and ionized atmosphere have on electron temperature determination, has been published elsewhere (References 6 and 9).

Electron temperature is computed from the characteristics of the collector current as the potential of the grid relative to the satellite skin is varied. The experimental volt-ampere curve taken at the 1630 km altitude is illustrated in Figure 2. An electron temperature value of 1750° ± 200°K is computed from from the slope at negative potentials according to

$$T_e = \frac{e\,\Delta\phi_{gs}}{k \ln \frac{i_1}{i_2}} , \tag{1}$$

where $e$ is the electronic charge, $k$ is Boltzmann's constant, and $\Delta\phi_{gs}$ is the change in grid voltage between values of measured collector current, $i_1$ and $i_2$. The error quoted in the temperature is due to the limited resolution to which the curve can be read.

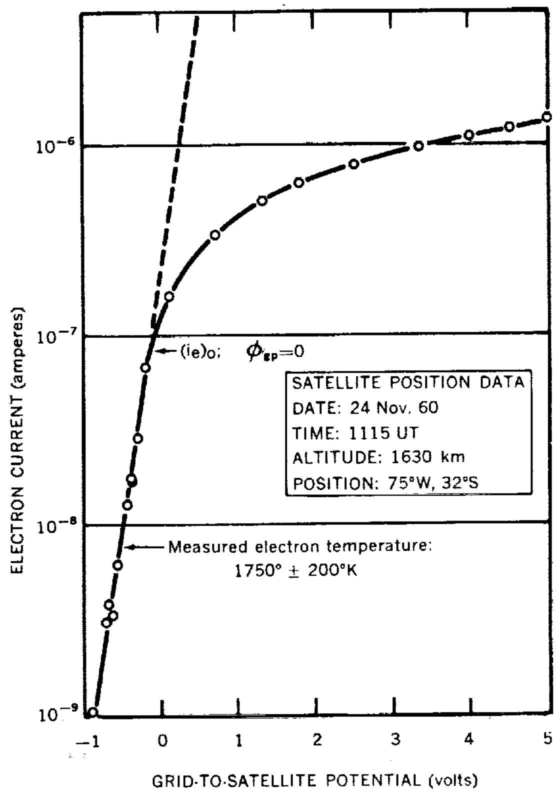


Figure 2 – Experimentally-obtained volt-ampere curve from the Explorer VIII two-element electron temperature probe

The volt-ampere curve can also be used to obtain an approximate value for the electron density $N_e$, according to

$$(i_e)_0 = \frac{e\left(\alpha_e N_e \bar{c}_e A\right)}{4}, \tag{2}$$

where $(i_e)_0$ is the collector current measured when the aperture grid is at the plasma potential ($\phi_{gp} = 0$), $A$ is the area of the collector, $\alpha_e$ is the electrical transparency of the grid, and $\bar{c}_e$ is the mean electron velocity computed from the measured electron temperature. The grid's electrical transparency was calibrated in flight by comparing the collector current with the current to an isolated conducting plate mounted flush with the satellite skin. The measured electron density of $1.2 \times 10^4/\mathrm{cm}^3$ agrees very well with the positive ion concentration measured with the ion trap to be described shortly.

In accordance with Ichimiya et al. (Reference 10) the measured satellite potential computed from Figure 2 is +0.1 volt. However, because of the induction effect of the earth's magnetic field, the satellite surface is not equipotential, as was postulated theoretically by Beard and Johnson (Reference 11) and verified experimentally by Bourdeau, et al. (Reference 6). This, in addition to uncertainties in the calibration for the absolute value of $\phi_{gs}$, results in an estimated error of ±0.3 volt in the knowledge of the potential at any specific satellite location. This error is not present in the electron temperature determination. Since the electron temperature is involved in computing electron density from the measured collector current, the volt-ampere curve in Figure 2 is internally consistent.

## MEASURED RATIOS OF IONIC CONSTITUENTS

The ratios of ionic constituents were measured by a retarding potential experiment illustrated schematically in Figure 3. The sensor contains three parallel electrodes. Its aperture is flush with and electrically connected to the satellite skin. A negative bias on the inner grid suppresses photoemission from the collector and removes incoming electron current. Consequently, the collector current is responsive only to the flow of positive ions

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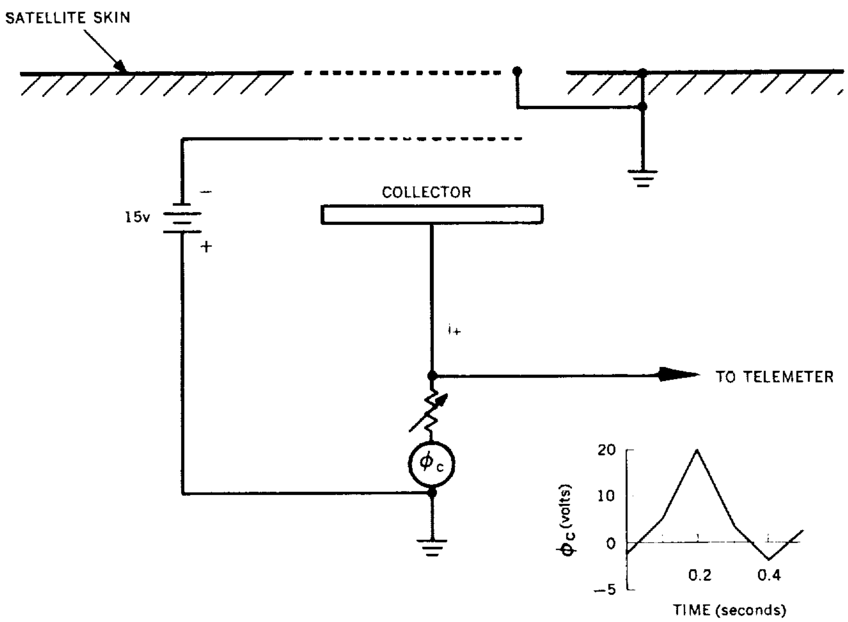


Figure 3 – Retarding potential experiment used on the Explorer VIII Satellite

from the ionosphere to the satellite. The ratios of ionic constituents are determined from the characteristics of the current to the collector as the latter's potential is varied in accordance with the waveform illustrated in Figure 3.

As the collector potential increases, the ions are slowed down; and those whose kinetic energies relative to the satellite are less than the potential energy of the collector with respect to the plasma are turned back. Consequently, the measured ion current is a function of both the retarding potential and the relative velocity between the ions and the satellite.

For a spacecraft traveling fast enough to make the thermal motions of the ions negligible, the kinetic energy of an ion relative to the satellite is proportional to the square of the satellite velocity. Specifically, the collector potential $\phi_c$ (relative to the plasma) at which all the ions of mass $M$ are retarded is given by

$$\phi_c = \frac{M\,(V\cos\theta)^2}{2e}\,, \tag{3}$$

where $V$ is the known satellite velocity and $\theta$ is the angle between the normal to the sensor and the direction of motion of the satellite.

For the actual satellite case, the thermal velocity of the ions, which is in turn dependent on their mass $M$ and their temperature $T_+$, cannot be neglected. The behavior of the ion current for a single ionic constituent is then given by the following expression (Reference 1), which takes into account all values of satellite-to-ion velocity ratio as well as the angle $\theta$:

$$i_+ = \alpha_+ N_+ eA \left[ V \cos\theta \left( \frac{1}{2} + \frac{1}{2} \operatorname{erf} x \right) + \frac{a e^{-x^2}}{2\sqrt{\pi}} \right] , \tag{4}$$



where $\alpha_+$ is the known combined electrical transparency of the two grids, $N_+$ is the ion concentration,

$$x = \frac{1}{a} \left( V \cos\theta - \sqrt{\frac{2\phi_c e}{M}} \right) , \tag{5}$$

and

$$a = \sqrt{\frac{2kT_+}{M}} . \tag{6}$$

If more than one ion species is present, the total current is given by the sum of the individual ion currents as given in Equation 4, where the appropriate $M$, $a$, and $N$ must be used for each ion species. Theoretical curves for varying mixture ratios have been computed for given values of $V$ and $T_+$ and for $\theta = 0$. These are illustrated in Figure 4 for an oxygen-helium mixture and in Figure 5 for an oxygen-hydrogen mixture. The abscissa is the collector-to-plasma potential, and the ordinate is a normalized ratio of collector currents $i_+/i_0$ where

$$i_0 = (N_1 + N_2) \alpha_+ eAV \cos\theta , \tag{7}$$

and $N_1$ and $N_2$ are the number densities of the individual ion species. This is very nearly equal to the current for $\phi_c = 0$.

It can be seen that an oxygen-helium mixture is characteristically identified by an inflection point and an oxygen-hydrogen mixture by distinguishable plateaus. Computations from Equation 4 show that the shape of the retarding potential curve is relatively insensitive to ion temperature. Although this enhances the capability of the experiment as an ion spectrometer, it makes it difficult to verify the conclusion (presented in a later section) that the electrons and ions are in thermal equilibrium.

Figure 6 shows experimental values of $i/i_0$ as a function of $\phi_c$, obtained at an altitude of 1630 km on November 24, 1960. It is immediately apparent from the shape of the curve that an oxygen-helium mixture is indicated. The two superimposed theoretical curves were computed by using the known values for $V$ and $\theta$ at the time the experimental data

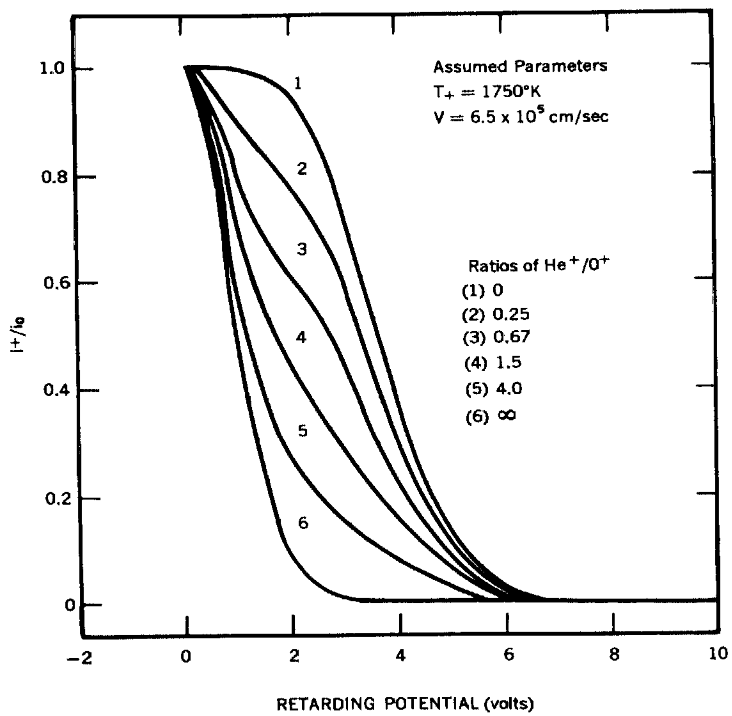


Figure 4 – Theoretical retarding potential curves for a binary mixture of helium and oxygen

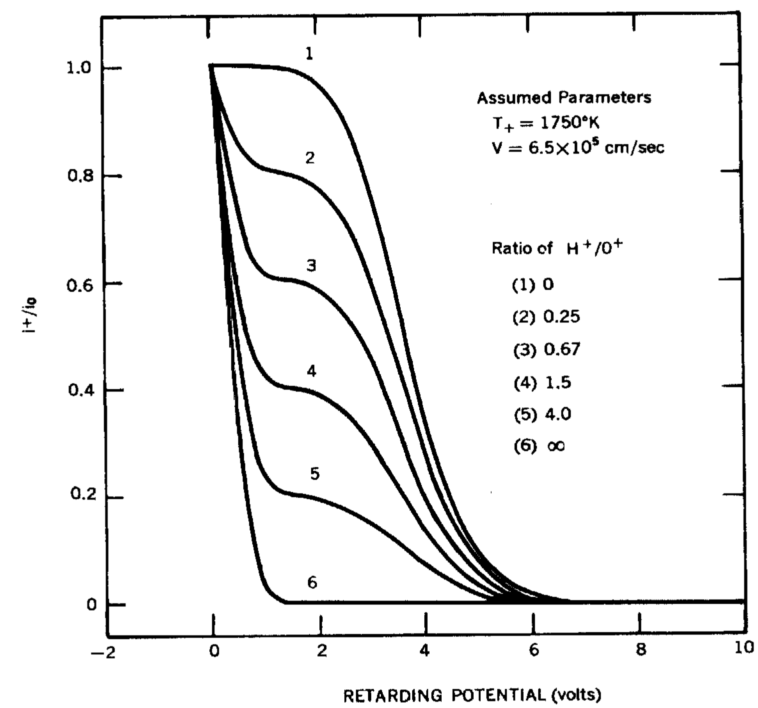


Figure 5 – Theoretical retarding potential curves for a binary mixture of hydrogen and oxygen

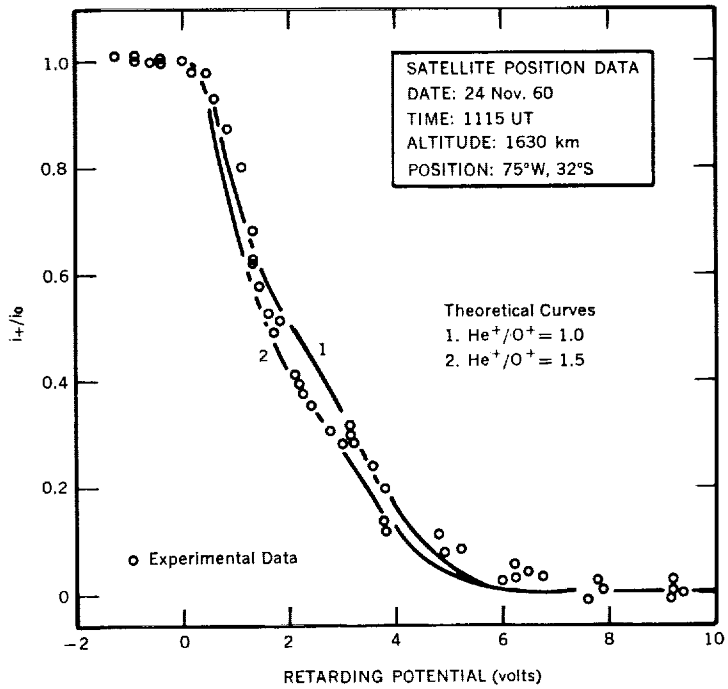


Figure 6 – Comparison of experimental and theoretical retarding potential curves for $He^+/O^+$ = 1.5



were obtained, and an ion temperature equal to the electron temperature measured by the probe described in the previous section. Since the experimental points lie between two theoretical curves for ratios of $He^+/O^+$ of 1.0 and 1.5, respectively, it is estimated that the actual ratio was 1.3 ± 0.3. The error spread is perhaps optimistic because the theoretical curves were computed on the assumption that $\theta$ is invariant, while $\theta$ varied experimentally from 0 to 25 degrees during the time required to obtain a volt-ampere curve. To reduce this sort of error spread, the two theoretical curves in Figure 6 were computed for $\theta$ = 15 degrees. The larger deviation of the experimental points from the theoretical curves at low values of $i_+/i_0$ is due to the effect of noise in the telemetry system at small signal levels.

In determining the experimental values of the collector-to-plasma potential, it is necessary to add the satellite-to-plasma potential algebraically to the known value of the collector-to-satellite potential. The ratio of $He^+/O^+$ quoted above is determined more accurately from the shape of the experimental curve than from the absolute position along the abscissa. To obtain the fit to the theoretical curves illustrated in Figure 4 requires a satellite-to-plasma potential at the sensor location of -0.2 volts, which is within experimental error of the value measured by the electron temperature probe. Even if the satellite potential were slightly positive (in which case some hydrogen ions would be retarded at the aperture grid), the conclusion that the $H^+$ concentration is smaller than that of $He^+$ or $O^+$ would be verified by the agreement between the electron density measured with the electron temperature probe and the measured ion concentration discussed in the succeeding section.



More retarding potential curves than that detailed in this report have been analyzed. To obtain accurate ratios of ionic constitutents, the sensor must be pointed within a few degrees of the velocity vector. Thus, only a small percentage of the retarding potential observations can be used for accurate analysis. Observations below 1000 km indicate a mean ionic mass of 16 A.M.U. (The ratio of light to heavy ionic constituents was less than 0.1, the limiting sensitivity of the instrument.) The shapes of other I-V curves obtained between 1000 and 1600 km also indicate an $O^+$-$He^+$ mixture rather than $O^+$-$H^+$. At altitudes above 1600 km the sensor orentation was, in general, unfavorable.

## MEASURED VALUES OF POSITIVE ION CONCENTRATION

The concentration of positive ions was measured by an ion current monitor whose sensor is mechanically identical to the retarding potential probe illustrated in Figure 3. It differs electrically in that the collector is maintained at the satellite potential at all times. A similar device was used successfully by Hanson and McKibbin (Reference 12) on an ARGO D-4 rocket flight subsequent to the launching of Explorer VIII. Hale (as reported in Reference 13) also carried out a successful experiment on a SCOUT rocket with an ion trap suggested by Pearse and Bennett.

If the satellite potential is such that no positive ions are retarded, the current measured by the ion current monitor when the sensor is pointed in the direction of motion is given by

$$i_+ = e\alpha_+ N_+ VA \cos\theta \ . \tag{8}$$

For the 1630 km altitude reported here, the computed value of $N_+$ derived from the peak ion current measured during one satellite revolution is $1.3 \times 10^4$ ions/cm$^3$. Both the ion current monitor and the retarding potential probe were located on the satellite equator (Figure 1); consequently, the satellite potential should be equal for the same sensor orientation. If the satellite potential at the equator were slightly positive, the quoted ion concentration value would contain only the contribution of helium and oxygen ions. However, the agreement between this value and the electron density measured by the electron temperature probe is an indication that hydrogen ions are less important than either helium or oxygen ions at altitudes below 1630 km.

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## UPPER IONOSPHERE MODEL BASED ON EXPLORER VIII DATA

On the basis of Explorer VIII data together with ionosonde data taken at the same time and approximate geographic location, it is now possible to derive an electron density profile which is internally consistent and in good agreement with helium-to-oxygen ion ratio postulated by Nicolet (Reference 14). This is illustrated in Figure 7.

From ionosonde data taken at 73°W and 36°S, a peak electron density of $10^6/cm^3$ at an altitude of 300 km is determined. These values correspond to a location roughly on the same magnetic field line with the satellite position. The two theoretical profiles shown in Figure 7 were computed for altitudes below 600 km and 800 km, respectively, on the basis of a Chapman distribution with a scale height corresponding to temperatures of 1600°K and 1750°K respectively. These two temperature values lie within the experimental limits of the electron temperatures measured on Explorer VIII. Also assumed are an average value for the acceleration of gravity of 770 cm/sec$^2$ and that $O^+$ is the predominant ion in the region below 800 km. The latter assumption was verified experimentally from previously reported Explorer VIII retarding potential data (Reference 15).

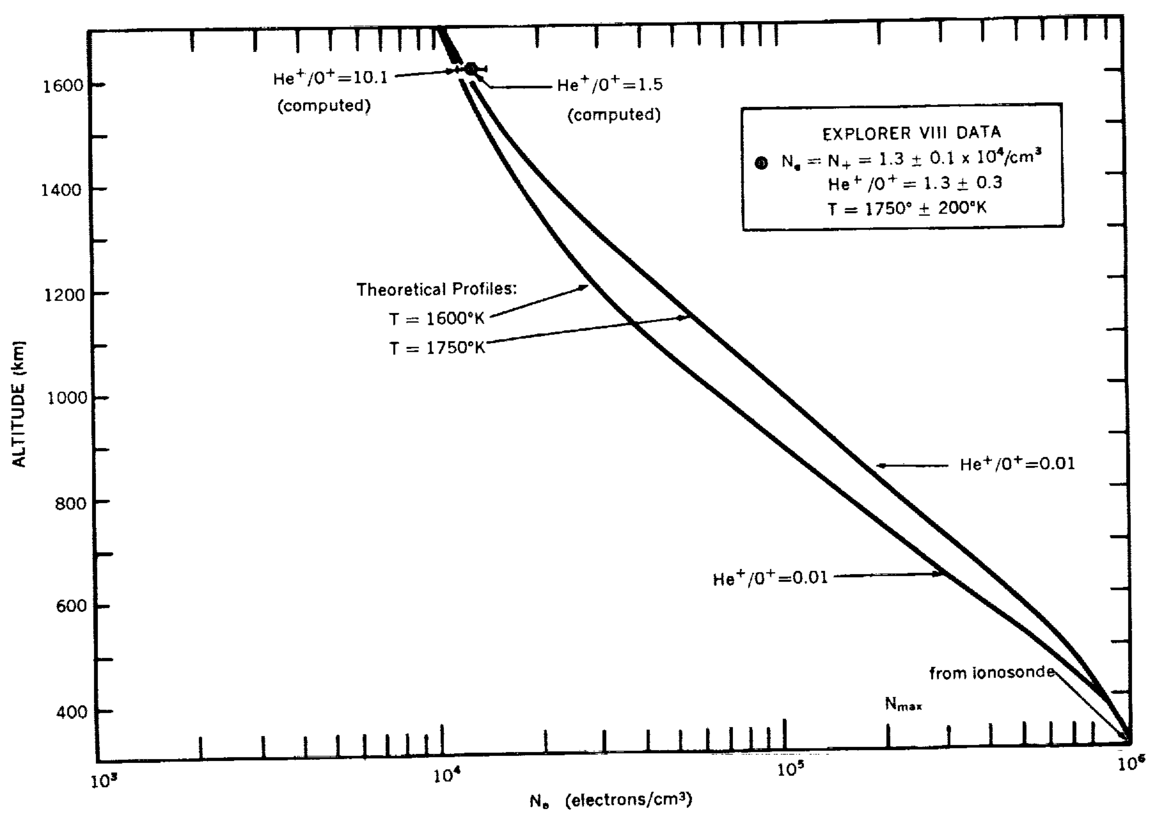


Figure 7 – Model of upper ionosphere based on Explorer VIII satellite data

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Above 600 km and 800 km, respectively, the two electron density profiles were computed from the following theoretical expression for an isothermal two-constituent upper ionosphere in diffusive equilibrium (Reference 15):

$$N(z) = N_0 \exp\left\{-\frac{1}{2}\left[\left(\frac{z}{H_1}\right) - \ln\left(1 + \eta e^{z/H_{12}}\right) + \ln(1+\eta)\right]\right\}, \tag{9}$$

where

$z = h - h_0$ is a height parameter measured from a reference level $h_0$,

$$H_1 = \frac{kT}{m(O)g},$$

$$H_{12} = \frac{kT}{\left[m(O) - m(He)\right]g},$$

$$\eta = \frac{n(He^+)}{n(O^+)} \text{ at } h_0,$$

and $g$ is the acceleration of gravity.

Two recent experimental results (References 12 and 17), have shown that the ionosphere above 400 km is isothermal and in diffusive equilibrium. In view of the fact that the location of the satellite measurements corresponds to a rather low geomagnetic latitude, it must be emphasized that a diffusive equilibrium distribution of the electrons and ions holds only along a magnetic field line.

In the computation of the electron density profile shown in Figure 7, the ratio $He^+/O^+$ must be $10^{-2}$ at 600 km for a temperature of 1600°K and at 800 km for 1750°K in order to fit the two profiles to the ion density measured at the satellite altitude. As was mentioned previously, the profiles were computed by using an average value for the acceleration of gravity over the altitude interval considered. If the altitude dependence of $g$ is taken into account (by expressing $z$ in Equation 8 in terms of geopotential altitude and using the surface value of $g$) the altitudes at which $He^+/O^+ = 10^{-2}$ would be reduced by about 50 km. The altitudes at which a ratio of $He^+/O^+$ is required to be $10^{-2}$ to fit the measured ion density are close to that postulated by Nicolet (Reference 14).

For the theoretical profiles, it is then computed that the ratios of $He^+/O^+$ at the satellite would be about 10 for the profile corresponding to $T = 1600$°K, and 1.5 for the 1750°K profile. Consequently, the latter is the most likely profile for the time and position at which the Explorer VIII data were taken, since it is consistent with the measured $He^+/O^+$ ratio as well as the measured electron temperature and ion concentration.

On the basis of this consistency it may also be concluded that in the upper ionosphere the electrons are in thermal equilibrium with the heavier constituents, as postulated by Hanson and Johnson (Reference 18) from theoretical considerations of the ionizing radiation and the energy transfer mechanisms. With reference to Figure 7, it is the sum of the ion (or neutral particle) and electron temperatures which determine the electron distribution with altitude for the general case. The profile was constructed on the assumption of thermal equilibrium by using the measured electron temperature. If the neutral or ion temperature were significantly lower than the measured electron temperature (absence of thermal equilibrium), the computed electron density would be correspondingly smaller than the measured electron and ion density observed at 1630 km. Thermal equilibrium in this altitude region has been postulated also by Jackson and Bauer (Reference 17) as a result of an electron density profile which they obtained with a cw propagation experiment and from a comparison of the diurnal variation of measured Explorer VIII electron temperatures (Reference 19) with kinetic gas temperatures deduced from satellite drag.

The characteristics of the profile corresponding to 1600°K are close to that inferred by Hanson (Reference 18) from Hale's ion density profile. Consequently, it is possible to explain the difference between Hanson's profile and that corresponding to the Explorer VIII data on the basis of a 150°K difference in the temperature of the upper ionosphere and a 200 km difference in the altitude at which $He^+/O^+ = 10^{-2}$.

There is agreement between the two profiles as to the main feature – that helium ions are an important constituent and that their concentration is approximately that postulated by Nicolet (Reference 14).

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IV. Bauer, S. J.
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Values of positive ion concentration ($N_+ = 1.3 \pm 0.1 \times 10^4$ ions/cm$^3$), electron temperature ($T_e = 1750^\circ \pm 200^\circ$ K), and the ratio of atomic helium to oxygen ions ($He^+/O^+ = 1.3 \pm 0.3$), measured by three separate experiments at an altitude of 1630 km on the Explorer VIII satellite (1960$\xi$), are presented. These, together with ionosonde data, are shown to be consistent with a model of an isothermal upper ionosphere in diffusive equilibrium. This model implies that hydrogen ions are less important than both helium and oxygen ions at altitudes below 1600 km. The measured ratio of helium to oxygen ions is consistent with that postulated by Nicolet in 1961.

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